Interpretation of a microwave induced current step in a single intrinsic Josephson junction on a Bi-2223 thin film

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Thin stacks consisting of a single intrinsic Josephson junction on (Bi,Pb)-Sr-Ca-Cu-O thin films are investigated under the influence of external microwave fields. The I-V-characteristic shows a single resistive branch, a clear superconducting gap edge structure and a pronounced current step in external microwave fields. With increasing irradiation power it shifts to higher voltages, while the height of the step remains practically unchanged. In a numerical simulation including an ac-magnetic field parallel to the superconducting layers the experimental features of the structure can be explained by a collective motion of Josephson fluxons.

1. INTRODUCTION

It is well established now that the electronic c-axis transport in the superconducting state of high-T_c-superconductors (HTSC) like $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223) is determined by an intrinsic Josephson effect between the superconducting CuO_2-layers [1–5]. Recently, the microwave properties of these materials attracted considerable attention for future electronical applications like high frequency oscillators and high-speed digital devices. In this context microwave phase-locking [6], the emission of Cherenkov radiation [7] and collective fluxon motion [8] have been reported. However, due to the strong (inductive) coupling of the dynamics in different intrinsic Josephson junctions (ITJJ) a detailed analysis is complex. Therefore the study of recently fabricated samples consisting of a *single* junction is interesting, as it rules out the influence of interactions and heating effects.

2. EXPERIMENTAL RESULTS

We have prepared Bi-2223 thin films using Pb dopant as a stabilizer of the 2223 phase on a MgO(100) substrate. Details of the preparation technique and the experimental setup can be found elsewhere [9,10]. SEM, AFM and TEM analysis reveal that the prepared films were composed of crystal grains with a size of 4μm $\times$ 4μm and a roughness of about 1.8nm, which is one half of the c-axis lattice constant. The mesa-type stack structures with an area of $\sim 2\mu$m $\times$ 2μm were fabricated using standard photolithography and Ar-ion milling techniques. The I-V-curve of the stacks show 1-3 branches, which is consistent with the height of the stack as expected from the etching rate of $\sim$ 10nm/min.

Typical parameters of the junctions are as follows: critical temperature $T_c \sim 100K$, critical current density $j_c \sim 4 \cdot 10^3$A/cm^2. In contrast to stacks with a lot of ITJJs, it is possible to extract the normal junction resistance $R_n \sim 32\Omega$, the $I_cR_n \sim 5.1$mV product and the value $\Delta_0 \sim$ 37.5mV of the superconducting gap directly. Due to the nonlinearity of the I-V-curve the characteristic frequency f_c and the McCumber parameter β_c are strictly speaking not well defined material parameters, but they can be roughly estimated from R_n ($f_c = 2eI_cR_n/h \sim 2.5$THz) or from the

Figure 1. I-V-characteristic at 4.2K of a mesa with dimensions of 2μm $\times$ 2μm showing a single ITJJ. The experimental curve coincides with the theoretical one assuming a d-wave order parameter.

return current I_r (from the resistive to the superconducting state): $\beta_c = (4I_c/\pi I_r)^2 \sim 16.6$ [11]. The contact resistance of the Au/Bi-2223 interface was evaluated by the slope of the superconducting branch at 4.2K as $\sim 8 \cdot 10^{-8}\Omega\mathrm{cm}^2$. This value for the contact resistance is several orders of magnitude smaller than in previous experiments [1,4] and essentially eliminates possible nonequilibrium effects due to heating.

Figure 2. (top) Dependence of the current step structure on the microwave power P, which gradually increases from (a) to (d) (5mV/DIV for voltage and 50μA/DIV for currents).
(below) Voltage position V_m (a) and height I_m (b) of the current step as a function of $\sqrt{P}$.

Figure 1 shows the I-V-characteristic at 4.2 K of the thinnest fabricated stack with a single resistive branch corresponding to a single unit cell. The I-V-curve can be well reproduced theoretically assuming a d-wave order parameter $\Delta(\theta) = \Delta_0 \sin(2\theta)$ and a parallel resistance of 7.8Ω.

We have also studied the behaviour of the single ITJJ in external microwave radiation in the frequency range up to $f_c \sim 27$GHz, which is two orders of magnitude smaller than the characteristic frequency $f_c \sim 2.5$THz. In this case the maximum current $I_{s,\max}$ of the superconducting branch decreased monotonically with increasing microwave power [8].

In addition to this, we observed a pronounced current step structure in the I-V-curve at a certain voltage V_m. For amplitudes, which suppress the superconducting branch completely, this structure appears in the lower millivolt range. Figure 2 shows that with increasing power P of the microwave irradiation the step structures shift to higher voltages $V_m \sim \sqrt{P}$, while the height I_m of the step remains practically unchanged.

3. DISCUSSION

Shapiro steps can be ruled out as an explanation of this phenomenon, because they are expected at voltages $V_{\mathrm{sh},n} = n\hbar\omega_{\mathrm{rf}}/2e$, which are integer multiples of the voltage $\omega_{\mathrm{rf}}/2e \sim 34\mu V$. As the difference of their voltages is two orders of magnitude smaller than V_m, this interpretation becomes very unlikely, as it would predict a series of high-order Shapiro steps with rather low amplitude instead of one pronounced step.

On the other hand, the lateral size $L_{ab} \sim 2\mu m$ of the stack is still larger than the typical size $2\lambda_J \leq 0.6\mu$m [12] of a Josephson vortex, which allows for fluxon motion parallel to the layers. It is thus reasonable to associate the observed step structure with some kind of collective vortex flow.

Figure 3. Comparison of experimental (left) and theoretical (right) I-V-curve of the single ITJJ with $f_{\mathrm{rc}} \approx 27$GHz for different amplitudes H_{ac} of the ac-magnetic field ($\gamma = I/I_c$, $\nu = \hbar/2e\langle\dot{\Phi}\rangle_t$, $H_{ac0} = 3.5/5 \hat{=} 2/2.8T$).

A complete model of the phase dynamics under the influence of external microwave irradiation would include the detailed discussion of the (unknown) boundary conditions on the surface of sample in order to determine the magnitude of the induced electric and magnetic fields both parallel and perpendicular to the superconducting layers.

Figure 4. Snapshots of the simulated supercurrent distribution $\sim \sin\Phi(x,t)$ in region A/B (left/right) (cf. Fig. 3). Open/closed circles represent the center of fluxons/anti-fluxons moving to the right/left respectively. The plots (a)-(e) are taken at different (not equidistant) time steps ($H_{\mathrm{ac0}} = 2T$).

Also various pinning mechanisms should in principle be taken into account.

For the reproduction of the experimental features presented above it will be sufficient to consider the effect of ac-magnetic fields $H_{\mathrm{ac}}(t) = H_{\mathrm{ac0}}\sin(\omega_{\mathrm{rf}}t)$. Note that the influence of an external magnetic field H_{ac} is formally equivalent to currents injected parallel to the layers. It also turns out in the simulation that an externally applied oscillating c-axis current $I_{\mathrm{ac}}(t)$ is unable to reproduce the experimental data correctly. The nonlinearity of the quasiparticle current is modelled as in [5,13].

Figure 3 compares the experimental step structure and the theoretical simulation using the parameters given above. Thereby both the dependence of the critical current I_c and of the voltage V_m and the height I_m on the external microwave power $P \sim H_{ac0}^2$ can be successfully reproduced.

As the typical frequencies used here are much smaller than the plasma frequency, the external microwaves have similar effects as static external fields and consequently do not depend on the exact value of the oscillation frequency.

As a consequence, the behaviour of the observed structure can be understood in terms of well known features of the flux-flow step in high magnetic fields [7,8]: $V_m = BsL_{ab}$ (s: distance of superconducting layers) and $I_m/I_c = c_s/L_{ab}f_c \sim 0.06$. Physically the step structure occurs when the Josephson vortices created by the external field approach their limiting Swihart velocity $\bar{c} \approx 2-5\times 10^5$m/s [7,14].

The numerical solution of the Sine-Gordon equation allows to discuss the supercurrent distribution $I_c \sin\Phi$ in the regions A and B as marked in Fig. 3. Open/closed circles in Fig. 4 represent the center of vortices/anti-vortices respectively and the plot (a)-(e) are taken at different (not equidistant) time steps. In contrast to the static case, the direction of moving fluxons will change with the external frequency ω_{rf}, changing the polarity according to the (alternating) direction of the external field $H_{ac}(t)$.

In region A (cf. Fig. 4) the phase is increasing linearly $\Phi(x,t) \sim \Phi_0 + kx$, which corresponds to a very homogeneous field distribution in the stack. On the other hand, in region B more pronounced kinks in the phase can be found, which account for a loose array of vortices with periodically oscillating relative distance of the fluxons.

4. CONCLUSIONS

The successful fabrication of single intrinsic junction stacks on Bi-2223 thin films with low contact resistance and $I_cR_n \sim 5.1$mV has been reported. Due to this fact we were able to study the properties of a single junction without interference with different junctions in the stack and eliminating the influence of heating. Under microwave irradiation, we observed a pronounced step in the I-V-characteristic of the single ITJJ in the lower millivolt range well below the superconducting gap edge. Its voltage position changes linearly as a function of the square root of the irradiated microwave power, while the step current remains constant. This behaviour could be qualitatively reproduced by numerical simulations in an external ac-magnetic field parallel to the layers, which show a collective motion of vortices in alternating directions.

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